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CHEMICAL WEATHERING ASSOCIATED WITH TAFONI AT PAPAGO PARK, CENTRAL ARIZONA

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ABSTRACT

Papago Park, Arizona, is a pediment-inselberg complex that hosts a variety of well developed tafoni and alveolar weathering forms. The purpose of this paper is to analyse the nature of chemical weathering associated with the tafoni using backscatter electron microscopy (BSE) and quantitative wavelength dispersive X-ray analysis (WDS). Calcium-rich and iron-rich coatings occur on the outer shells of the tafoni. Calcium carbonate precipitation within mineral microfractures occurs on the underside of the tafoni. Chemical weathering of primary mineral grains provides a source of material found in the coatings. The WDS analyses show a near-complete lack of salt-forming elements.

KEY WORDS tafoni; backscatter electron microscopy; chemical weathering

INTRODUCTION

The purpose of this paper is to investigate the nature of chemical weathering associated with tafoni developed at Papago Park in central Arizona. Tafoni are small holes or caves on the surface of a rock formed by weathering. They differ from weathering pans or hollows in that they form in a vertical plane. This is in contrast to pans that form on a primarily horizontal plane. The formation of tafoni has been debated for many years (Blackwelder, 1929; Twidale and Bourne, 1975; Conca and Rossman, 1982; Mustoe, 1983; Cooke *et al.,* 1993; Mustoe, 1983) with no consensus on their origin. The presence of tafoni in desert environments has been used to indicate both landscape antiquity (Büdel, 1982) and episodic exposure of land surfaces (Twidale and Bourne, 1975). Tafoni formation has been attributed to salt weathering (Winkler, 1979; Mustoe, 1983; Butler and Mount, 1986; Goudie, 1986) while other investigators have looked at the possible role of clays, aspect, and biogeochemical weathering by lichens (Dragovich, 1969; McGreevy and Smith, 1984). Papago Park was selected for this study because of the large number of tafoni and the simple local geology.

Papago Park is a pediment–inselberg complex composed of mid-Cenozoic debris-flow breccia overlying pre-Cambrian granite (Nations and Stump, 1981). This same granite is the principal rock type found as cobbles in the breccia. The cobbles vary in size but are typically in excess of 5 cm with smaller mineral crystals occurring in inter-cobble voids. The materials in the breccia are completely unsorted. The breccia matrix is calcium carbonate. There are minor outcrops of meta-rhyolite and sandstone in the park. Tafoni occur almost exclusively in the breccia (Figure 1). The regional climate is currently arid with a precipitation range of between 170 mm and 220 mm per year. The vegetation is typical of the Sonoran Desert, consisting of scattered creosote (*Larria tridentata*), brittlebush (*Encelia farinosa*) and barrel cactus (*Ferrocactus wislizeni*) while the gullies that dominate the drainage support small communities of palo verde trees (*Cercidium microphylum*). The rocky slopes are devoid of woody vegetation and have only a limited lichen cover.

The tafoni chosen for this study is at the top of a large eroded joint plane on the west side of South

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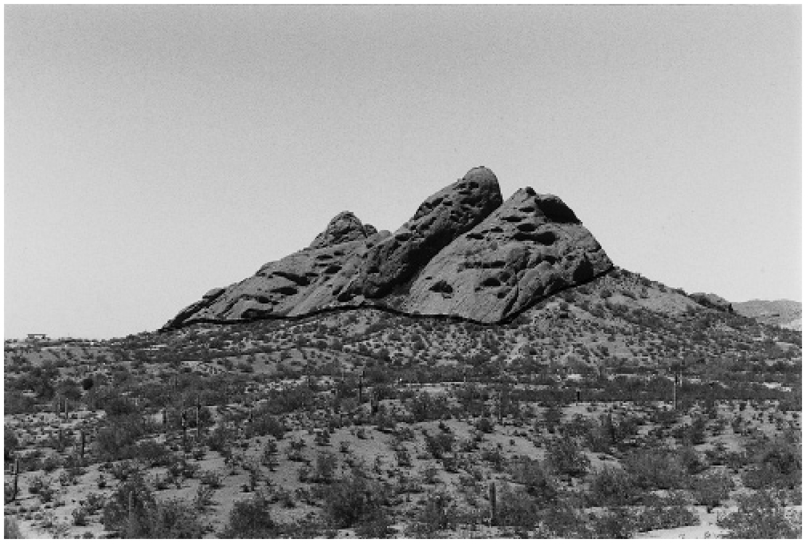

Figure 1. A view of Papago Park from the south showing the large number of tafoni on the surface of the butte. Resistant debris-flow breccia overlying less resistant Pre-Cambrian granite has caused the sharp change in slope. The breccia hosts the tafoni while the granite erodes into low-angle pediments. The line drawn on the image marks the contact between the breccia above and the granite below

Barnes Butte. The cavern is approximately 2·5 m across, 1·5 m in height, 1 m deep and has a southwesterly aspect (Figure 2a,b). The outer surface of the tafoni has a few small colonies of lichen. The underside, which is completely devoid of lichen, has a surface composed primarily of exposed granite cobbles. There is a small amount of rock meal on the floor of the tafoni (Figure 2b).

METHODS

Three sample sets consisting of between eight and 12 chips each were collected with a hammer and chisel from the outer 10 mm of the rock surface. Areas of obvious anthropogenic modification (e.g. spray paint) were avoided. All samples were collected from a single tafoni to compare several positions: the underside of the tafoni, the outside of the tafoni, and from several cobbles in the breccia matrix in the transition area between the upper and inner surfaces (Figure 2b).

Samples were prepared for analysis on the electron microprobe by embedding them in resin. Cross-sections were prepared by removing material with successive grit sizes of sandpaper. A scratch-free surface was obtained using 5.0 μm and 0.3 μm aluminium powder polish. The samples were coated with 20 nm of carbon to prevent electron charging. The samples were analyzed on a JEOL JXA 8600 Electron Microprobe equipped with a backscatter electron detector (BSE) and wavelength dispersive X-ray spectrometers (WDS).

A backscattered electron image records differences in the chemical composition. Weathering pores appear black on the image. Bright areas are composed of elements with a higher atomic weight, like iron. Wavelength dispersive analysis is a quantitative measure of elemental abundance, traditionally reported as oxide weight percentage. The sample sets were analysed by looking for similarities and differences in weathering features between the sample locations.

RESULTS AND DISCUSSION

The sample locations on the tafoni showed markedly different weathering features. Minerals incorporated in the breccia matrix are weathering along grain boundaries and mineral cleavage planes.

(a)

(b)

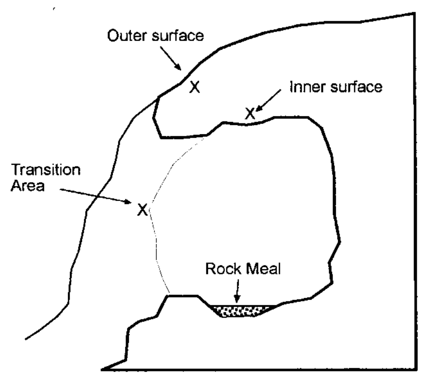

Figure 2. (a) The tafoni selected for this study. Note the variation in clast size and the unsorted nature of the breccia. (b) Diagram of the tafoni showing sample locations. Rock meal has been preserved in topographic low areas or behind obstructions

The outside of the tafoni is commonly covered with chemical coatings while the underside displayed granular disintegration and precipitation of calcium carbonate in microfractures. All of these components of the weathering system are working together to form the tafoni present on Papago Park.

Mineral grains taken from rock fragments in the breccia display advanced weathering of plagioclase, orthoclase and biotite (Figures 3A, 3C, 4A and 4C). The weathering of the plagioclase and orthoclase occurs when the mineral grains are repeatedly exposed to moisture. This causes the mineral grain to dissolve, forming voids or holes in the crystal. Pores repeatedly exposed to water gradually grow in size, exposing a larger surface area to water causing a positive feedback of increasing weathering rates. The biotite appears to weather by hydration along mineral cleavage planes (Nahon, 1991). The expansion of the mineral structure during hydration could apply enough pressure to wedge material loose from the rock surface (Figure 4C, centre of the image).

The outer surface of the tafoni displays 25 μm to 100 μm thick calcium-rich and iron-rich coatings (Figures 3A, 3B, 5 and 6). A combination of weathering in primary mineral grains and breccia matrix is a possible source for the material in the coatings. It is proposed that this process begins beneath the surface with raw materials being transported to the surface by capillary flow. This dissolved material is

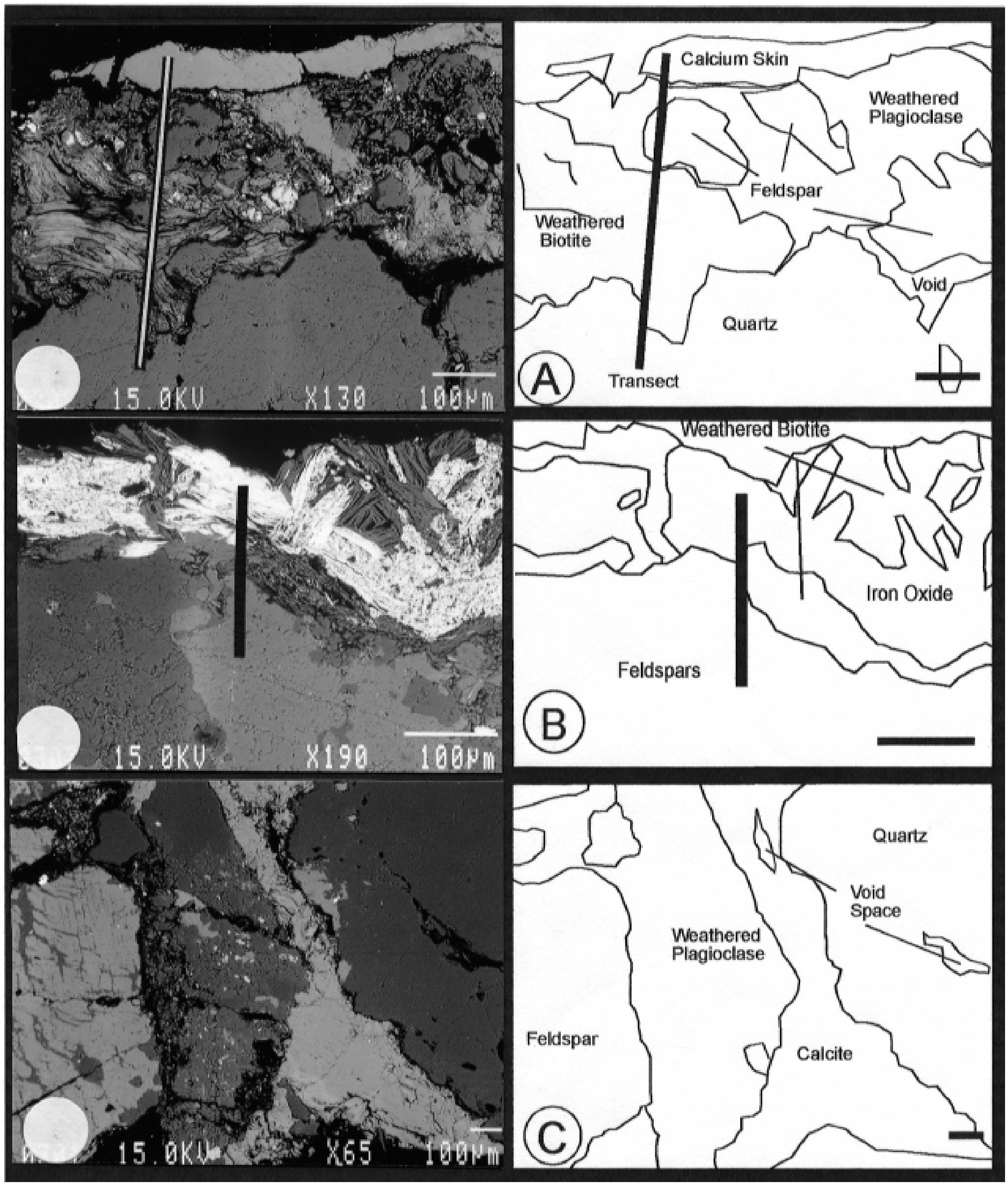

Figure 3. Micrographs from sites on the tafoni showing different weathering features. Maps of the mineralogy and important features aid interpretation. (A) An area of weathered biotite (left of image) and feldspar (upper right of image) covered by a calcium-rich coating that is about 50 μm thick. The weathered pores are black areas on the image in the centre of mineral grains. The line through the image shows the location of an electron microprobe transect (see Figures 6 and 7). The transect runs from the top of the image to the bottom. The sub-aerial surface is at the top of the image. (B) Weathered biotite (top right of image) grains are surrounded by an iron-rich coating 50 μm to 100 μm thick that has in-filled void spaces in the mica. The line shows the location of a probe transect that runs from the top of the image to the bottom (see Figure 5). The sub-aerial surface is at the top of the image. (C) A weathering feldspar grain in the centre of the image. The sample is being split in two by a wedge of calcium carbonate that has been reprecipitated into a fracture in the mineral grain

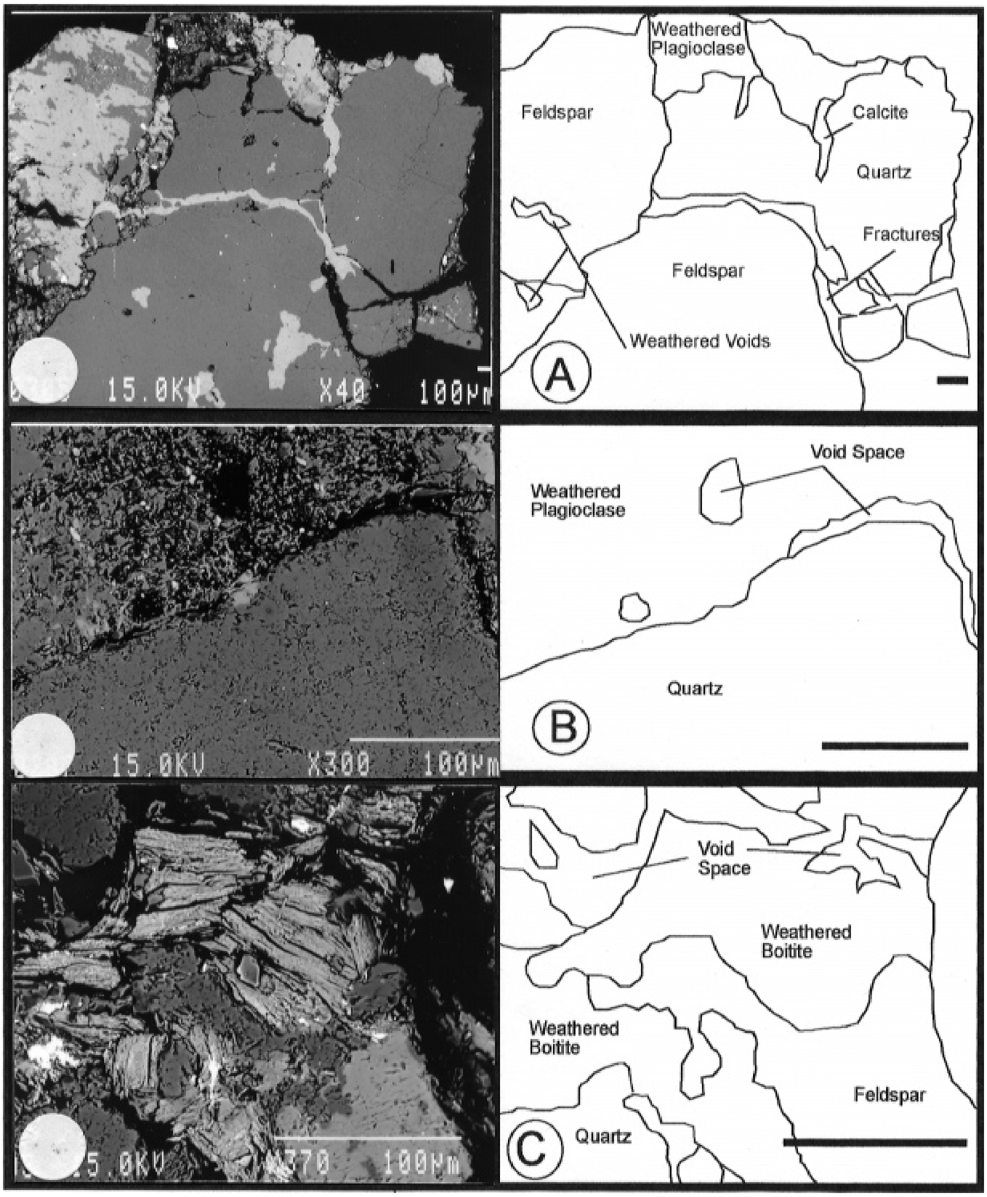

Figure 4. Micrographs from sites on the tafoni showing different weathering features. Maps of the mineralogy and important features aid interpretation. (A) A feldspar grain being wedged apart by calcium carbonate that is reprecipitating in the fractures in the mineral grain. The sub-aerial surface is at the right side of the image. (B) A plagioclase grain that is weathering along the grain boundary. Increased porosity in the mineral grain at the top of the image. Contrast this with the less weathered area in the lower part of the image. This increase in porosity is due to the dissolution of material at the boundary of the plagioclase grain. (C) Weathering of a biotite grain that is expanding along the cleavage planes of the mineral. The weathered area can be seen as a black area inside the mineral grain

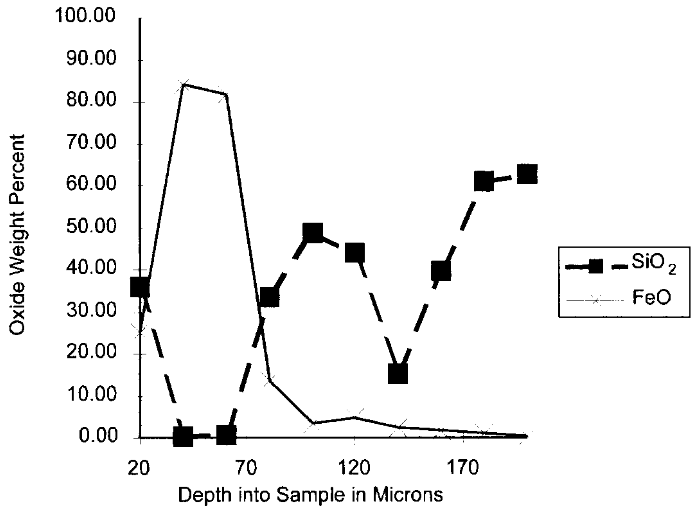

Figure 5. Iron and silica concentrations along the microprobe transect in Figure 3B. The concentration of iron in the bright coating averages 80 per cent to 85 per cent. The concentration of iron then drops sharply to around 5 per cent. At about the same point on the probe transect the concentration of silica increases from less than 1 per cent to approximately 60 per cent.

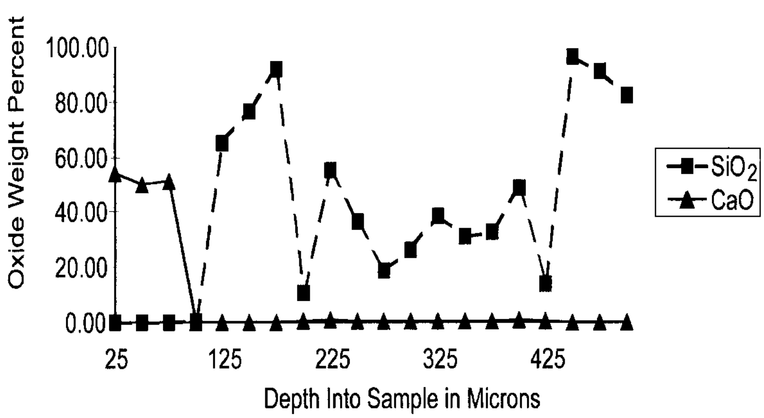

Figure 6. Calcium and silica concentrations along the microprobe transect in Figure 3A. The concentration of calcium in the coating averages 50 per cent to 55 per cent and silica is almost completely absent. Then the concentration of calcium drops to negligible levels and silica becomes much more abundant

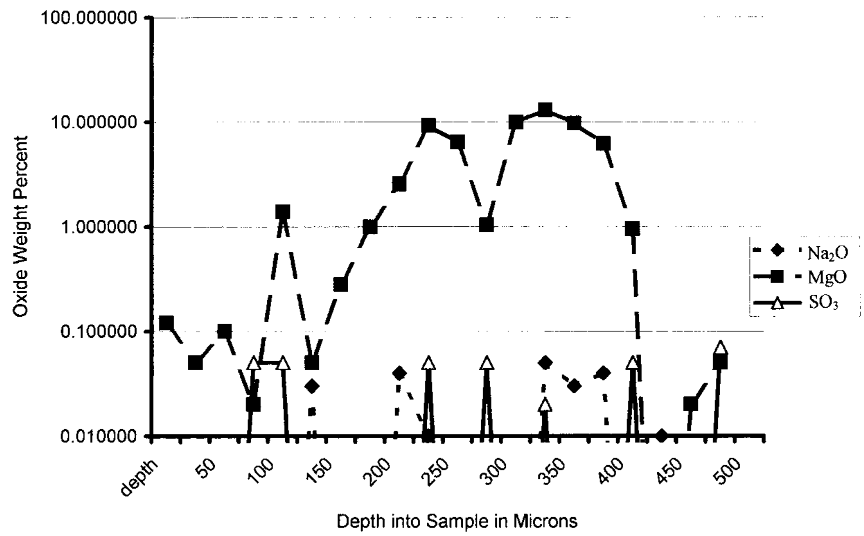

Figure 7. Concentrations of some of the most common salt-forming elements along the microprobe transect in Figure 3A. The elements in this graph are sodium (Na_2O), magnesium (MgO) and suphur (SO_3). These elements are shown because they are either the cation or anion of all major salts involved in chemical weathering. The graph is a log scale because the concentration of these elements was at or below the limit of detection, a function of the instrumentation on the probe. The transect in Figure 3A was chosen for presentation because it has the highest concentrations of these elements. The higher concentrations of magnesium could be due to the presence of the element in the biotite. Because of the lack of associated sulphur it is not believed to be a salt

precipitated on the surface as a rock coating. These coatings also appeared to be holding material onto the surface that would not normally remain adhered (Figure 3A, left-hand side of the image). These surface coatings would then appear to have a case-hardening effect on the surface (Conca and Rossman, 1982).

The underside of the tafoni shows precipitation of calcium carbonate into microfractures in the mineral grains (Figures 3C and 4A). This precipitation has a wedging effect on the mineral grains, degrading the grain-to-grain cohesion of the rock. The expansion of biotite mineral grains during weathering in combination with the calcium carbonate being precipitated in the microcracks could cause enough internal pressure to remove surface material by mechanical wedging (Péwé, 1987). Once material is loosened it would then be rapidly sloughed off. Conca and Rossman (1985) hypothesized that the formation of a hardened surface coupled with a softened interior could be responsible for the formation of small weathering features. In these tafoni the core softening would occur with the removal of the cementing agent from the breccia.

Aeolian dust could play a role in the formation of these coatings. The chemistry of the dust found in the Phoenix is typically high in calcium (Péwé *et al.*, 1981), therefore it could be a source of calcium for the coatings. However, if aeolian dust were the source of the constituent materials of the coatings, some detrital mineral grains would be incorporated into the coatings. Yet, the micrographs show that the coatings are homogeneous in nature (Figure 3A and 3B). This indicates precipitation of a solution derived from components of the adjacent rock material.

It should also be noted that no rock varnish was found on the tafoni either visually or microscopically despite the fact that it is a common rock coating in the Sonoran Desert (Elvidge, 1979). This is due either to an unfavourable environment for varnish production, or to the surface eroding faster than varnish formation can take place. If the surface is sloughed faster than varnish formation occurs this has implications on the rates of tafoni formation. Dorn and Meek (1995) found varnish formed on 40-year-old mine tailings. With a lack of desert varnish on the tafoni, the antiquity of these forms is suspect. In

addition, the presence of rock meal may indicate that these forms are currently under development. This is contrary to the idea that they are relict forms (Twidale and Bourne, 1975).

The formation of tafoni has been attributed to many different mechanisms, but crystallized salt has been one of the most frequently invoked. Salt is one of the most effective weathering agents in arid environments both through physical weathering by the precipitation of salt grains in cracks and through enhanced chemical weathering (Butler and Mount, 1986; Goudie, 1986; Mustoe, 1983). Owing to the limitations of the microprobe, it was necessary to select a relatively small number of elements for analysis. The elements that were analysed included either the cation or anion of the common types of salt found in desert environments (Goudie, 1986; Goudie and Viles, 1997). These elements are sodium, magnesium, sulphur and calcium. None of the samples analysed exhibited any visual evidence of salt crystal formation. The WDS abundance of the salt-forming elements was at or just above the limit of detection in all of the samples (Figure 7).

In summary, the weathering at Papago Park is characterized by precipitation of calcium-rich and iron-rich surface coatings and reprecipitation of calcium carbonate into microfractures in mineral grains. Weathering of the primary mineral grains found in the breccia and dissolution of the matrix cement could provide the materials that have been incorporated in the weathering processes. The calcium carbonate that has precipitated on the outer rock surface has led to differential hardness that allowed tafoni to form on the buttes. Salt weathering does not play a major role in the formation of this tafoni.

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